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Kramer, A.F.; Hahn, S.; Irwin, D.E.; Theeuwes, J.

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Attentional Capture and Aging: Implications for Visual Search Performance and Oculomotor Control

Arthur F. Kramer, Sowon Hahn, and David E. Irwin
University of Illinois at Urbana-Champaign

Jan Theeuwes
Vrije Universiteit

Two studies examined potential age-related differences in attentional capture. Subjects were instructed to move their eyes as quickly as possible to a color singleton target and to identify a small letter located inside it. On half the trials, a new stimulus (i.e., a sudden onset) appeared simultaneously with the presentation of the color singleton target. The onset was always a task-irrelevant distractor. Response times were lengthened, for both young and old adults, whenever an onset distractor appeared, despite the fact that subjects reported being unaware of the appearance of the abrupt onset. Eye scan strategies were also disrupted by the appearance of the onset distractors. On about 40% of the trials on which an onset appeared, subjects made an eye movement to the task-irrelevant onset before moving their eyes to the target. Fixations close to the onset were brief, suggesting parallel programming of a reflexive eye movement to the onset and goal-directed eye movement to the target. Results are discussed in terms of age-related sparing of the attentional and oculomotor processes that underlie attentional capture.

The interaction of top-down or goal-directed and bottom-up or stimulus-driven influences on attentional control has become a central issue in the study of visual attention (Martin-Emerson & Kramer, 1997; Theeuwes, 1995; Yantis, 1996). When driving an automobile in unfamiliar surroundings, people spend a great deal of time intentionally directing their attention to other automobiles, pedestrians, and features of the roadway that are important to the task of driving. However, salient features of the environment, such as a brightly flashing neon sign on the side of the roadway or a loud and abrupt protestation from one of two children sitting in the backseat arguing about a favorite toy, also appear to grab or capture people's attention regardless of the intention to attend to these events.

Indeed, the stimulus-driven capture of attention can have a positive influence on the task at hand, such as the sound of squealing tires alerting a driver to a potential accident ahead. However, attentional capture can also have negative consequences such as in the example above in which the driver is attending to the bright roadway sign rather than other automobiles. Analogs of these situations, that is, settings in which positive and negative consequences are realized with attentional capture, have been examined in the laboratory.

For example, Yantis and colleagues (Yantis & Hillstrom, 1994; Yantis & Jones, 1991; Yantis & Jonides, 1984, 1990) have conducted a number of studies in which subjects searched for a predefined target letter that could appear among other letters in a display. In each display, all but one of the letters were constructed by removing segments of figure eight premasks. These letters are referred to as "nononset stimuli." In addition, one new letter was added to the display concurrently with the removal of segments of the figure eight premasks. This new letter is referred to as an "onset." Although in these experiments the onset letter was no more likely to be the target than any of the other letters (i.e., the onset letter was the target $1/n$ trials, with n being equal to the total number of letters in a display), when the onset letter was the target, search performance was fast and independent of the number of letters in the display. These data have been interpreted as evidence that the onset or new object is always attended to first, that is, that abrupt onsets (or new objects) capture attention. Clearly, in these search experiments, attentional capture has a beneficial effect on performance by greatly decreasing search time for new objects.

However, there are also numerous empirical demonstrations of negative consequences of attentional capture. For example, Theeuwes (1994) had subjects search for a color singleton target (i.e., an item that appeared in a unique color) among other items in a display. On a subset of trials, an abrupt onset appeared simultaneously with the color change that revealed the location of the color singleton target. Although the abrupt onset (i.e., new object) never served as the target, search performance was slowed whenever the onset appeared. That is, the onset appeared to capture attention, which subsequently needed to be reoriented to the color singleton target, thereby slowing search. Remington, Johnston, and Yantis (1992) provided even stronger evidence that abrupt onsets capture attention in an involuntary, stimulus-driven fashion. In their search experiments, subjects were explicitly told that onsets would never cue the location of the target and were to be ignored. However, despite these instructions, search was slowed whenever

Arthur F. Kramer, Sowon Hahn, and David E. Irwin, Beckman Institute and Department of Psychology, University of Illinois at Urbana-Champaign; Jan Theeuwes, Cognitive Psychology, Vrije Universiteit, Amsterdam, the Netherlands.

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Correspondence concerning this article should be addressed to Arthur F. Kramer, Beckman Institute, University of Illinois, 405 North Mathews Avenue, Urbana, Illinois 61801. Electronic mail may be sent to akramer@s.psych.uiuc.edu.

an onset appeared in the display (also see Jonides, 1981; Theeuwes, 1995). In summary, these data suggest that abrupt onsets or new objects capture attention in an obligatory fashion, perhaps through the generation of an attentional interrupt that directs attention to the location of the onset, at least for a brief period of time (Martin-Emerson & Kramer, 1997; Yantis, 1996; however, see Folk & Remington, 1998; Folk, Remington, & Johnston, 1992).

Interestingly, although the phenomenon of attentional capture by abrupt onsets has been extensively examined, there has not, until recently, been any attempt to determine the influence of capture on oculomotor control. Thus, although the displays used in the studies described above have often been presented until a manual response is made, we know of no attempt to distinguish between the overt and covert capture of attention. The question of whether attentional capture by abrupt onsets influences oculomotor control as well as covert attention is important given previous studies of the relationship between the oculomotor and attentional systems.

Although the results of numerous tachistoscopic studies suggest that attention can be successfully oriented to locations in the visual field in the absence of accompanying eye movements (Eriksen & Yeh, 1985; LaBerge & Brown, 1989; Posner, 1980), studies that have examined the relationship between attention and oculomotor control in free-viewing situations have, in general, showed a close coupling between saccade programming and visual attention. For example, Deubel and Schneider (1996) found that letter identification performance was best when the letter to be identified was also the target of a saccade. Similarly, Hoffman and Subramaniam (1995) had subjects detect a visual target just before making a saccade and found that detection performance was best when the location of the target and the subsequent saccade were the same (see also Klein, 1980; Kowler, Anderson, Dosher, & Blaser, 1995; Remington, 1980; Sheliga, Craighero, Riggio, & Rizzolatti, 1997; Sheliga, Riggio, & Rizzolatti, 1995; Shepherd, Findley, & Hockey, 1986). Thus, it would appear that attention often precedes saccades to locations in the visual field.

Theeuwes, Kramer, Hahn, and Irwin (1998) recently examined the issue of the influence of attentional capture on oculomotor control with a paradigm like that illustrated in Figure 1. Observers were presented with six gray circles with small figure eight premasks inside. After 1,000 ms the color of five of the circles changed to red and segments of the figure eight premasks were removed to reveal letters. Subjects were instructed to move their eyes from the center of the display to the color singleton (i.e., the remaining gray circle) as soon as they detected the color change and to identify the letter inside the gray circle. On a subset of trials, a new red circle (i.e., an abrupt onset) appeared simultaneously with the color change, which cued the location of the color singleton target. The abrupt onset never served as the target.

When we designed the present study, we anticipated that we might observe one or some subset of several previously reported effects of attention on oculomotor control. For example, Sheliga, Riggio, and Rizzolatti (1994) reported slight deviations of the saccadic path (e.g., 10–15 min arc) when subjects were required to move their eyes either to a target located above or below fixation and simultaneously attend to a stimulus to the right or left of fixation (see also Sheliga et al., 1995). The saccadic path to the target was slightly displaced contralateral to the attended field, as if the eye movement systems were compensating for attentional attraction by the item that the subjects were covertly attending to as they were moving their eyes. We also suspected that we might observe a center-of-mass effect with the eye movements to the color singleton such that the initial saccade would end between the target and the onset distractor. Such a pattern of results has typically been observed when two targets are simultaneously presented in a display and subjects are given the choice of moving their eyes to either one of the targets (Findlay, 1997; Ottes, Van Gisbergen, & Eggermont, 1985; Viviani & Swensson, 1982). Finally, we anticipated that saccadic latency, that is, the time required to begin to move the eyes toward the target, would be increased in our study, as it has whenever subjects are required to inhibit an eye movement to a stimulus and move their eyes elsewhere in the visual field (i.e., in the antisaccade task; Guitton, Buchtel, & Douglas, 1985; Hallett & Adams, 1980).

The results that we did obtain in our paradigm were actually surprising. First, on approximately 35% of the trials, the eyes went directly toward the onset distractor, stopped for a brief period of time, and then went directly to the color singleton target. Furthermore, this pattern of results was obtained regardless of whether the onset distractor appeared close to the target or on the opposite side of the visual display (i.e., separated by 150° arc and 22° visual angle from the target). These results suggest that overt (i.e., the oculomotor system) as well as covert attention was captured by the appearance of a new but task-irrelevant object in the visual field.

Second, on the trials on which the eyes did initially go to the onset distractor, they stopped for only a brief period of time (i.e., 80% of the fixations were less than 100 ms) before moving directly to the color singleton target. Given that it takes approximately 150 ms to program a saccade (Abrams & Jonides, 1988; Becker, 1991; Salthouse & Ellis, 1980), the fixation duration data suggest that multiple saccades may have been programmed in parallel in our paradigm, one saccade to the color singleton target and the other saccade to the task-irrelevant onset. If the programming of the goal-directed saccade was completed first, the eyes would move directly to the color singleton target. However, if the programming of the reflexive saccade was completed first, the eyes would initially move toward the onset distractor and only later continue on to the target after the completion of the programming of the goal-directed saccade and the inhibition of the reflexive saccade. This proposal is consistent with neurophysiological and neuropsychological evidence that suggests that different oculomotor systems are responsible for voluntary (goal-directed) and reflexive (stimulus-driven) saccades (LaBerge, 1995; Pierrot-Deseilligny, Rivaud, Gaymard, Muri, & Vermersch, 1995; Schall, 1995). Goal-directed saccades depend on the functional integrity of a number of frontal and prefrontal areas, including the frontal eye fields, supplementary eye fields, and dorsolateral prefrontal cortex. On the other hand, reflexive saccades appear to be generated in a parietal-midbrain (i.e., superior colliculus) circuit. Indeed, the goal-directed system can suppress reflexive saccades via inhibitory influence from the frontal eye fields by way of the substantial nigra on the superior colliculus (Schall, 1995).

In summary, we believe that our attentional capture paradigm provides an important framework for the investigation of the interaction between goal-directed and stimulus-driven influences on the control of both covert and overt (i.e., eye movements) aspects of visuospatial attention. We now briefly review the liter-

ature on aging and attentional control before describing our studies.

Aging and Attentional Control

During the past decade, there has been an increasing interest in the examination of age-related differences in attentional control and more specifically age-related differences in the inhibition of task-irrelevant information. In large part, this interest can be attributed to Hasher and Zacks's (1988) proposal that age-related processing deficits in a variety of cognitive skills can be accounted for by a decrease in the efficiency of inhibitory processing during aging. More specifically, inefficient inhibition could result in failures of selective attention, which may in turn result in the intrusion of task-irrelevant information into working memory. The consequences of the entrance of task-irrelevant information into working memory could include both increased processing time and reductions in the recognition and recall of relevant information.

A thorough review of the evidence for and against this general inhibitory hypothesis is beyond the scope of this article (see Burke, 1997; McDowd, 1997; McDowd, Oseas-Kreger, & Filion, 1995; West, 1996; Zacks & Hasher, 1997, for reviews of this literature). However, within the context of visual attention, it is becoming increasingly apparent that specific rather than general inhibitory deficits are observed during the course of normal aging. For example, studies with one classic interference paradigm, the Stroop task, have shown reliably larger interference effects for older than for younger adults (Houx, Jolles, & Vreeling, 1993; Kwong See & Ryan, 1995; Rogers & Fisk, 1991; Spieler, Balota, & Faust, 1996; however, see Salthouse, 1996; Vakil, Manovich, Ramati, & Blachstein, 1996). In this task subjects are to verbalize the color in which a word is printed while ignoring the semantic content of the word. Older subjects take substantially longer to verbalize colors that are inconsistent with the semantics of the word (e.g., the word *blue* painted in red ink) than do younger adults. Thus, it would appear that older adults have more difficulty suppressing word meaning during color naming.

Studies of age-related differences in negative priming have produced more mixed results. In this paradigm, subjects are asked to respond to targets and ignore simultaneously presented distractor stimuli. The critical comparison is between trials on which a distractor from trial $n - 1$ becomes a target on trial n (the ignored repetition condition) and trials on which a different target and distractors are presented on trials n and $n - 1$ (the control condition). In initial studies, older adults failed to produce a difference between ignored repetition and control conditions, whereas younger adults showed slower responding to ignored repetition than they did to control trials (Hasher, Stoltzfus, Zacks, & Rympa, 1991; Kane, Hasher, Stoltzfus, Zacks, & Connelly, 1994; Tipper, 1991). These results were interpreted as indicating a failure of selective inhibition by the older adults (i.e., inhibition of the distractor on trial $n - 1$ results in slowed responding when the distractor becomes the target on trial n; Neill & Valdes, 1996). However, more recent studies (Kieley & Hartley, 1997; Kramer, Humphrey, Larish, Logan, & Strayer, 1994; Sullivan & Faust, 1993; Sullivan, Faust, & Balota, 1995) have shown equivalent negative priming effects for younger and older adults. Although there is yet no agreement on why this discrepancy exists in the literature between those studies that have shown age-equivalent negative priming effects and those that have not, possibilities include the sensitivity of the experimental design to the relatively small negative priming effect (on the order of 10–20 ms) and the difficulty of selection in the task (i.e., larger negative priming effects have been reported when selection of the target is difficult; Moore, 1994). That is, the greater variability in reaction time (RT) for older than younger adults may mask the negative priming effects for older observers. It is also conceivable that because the use of inhibition in the negative priming task is presumably effortful (Engle, Conway, Tuholski, & Shisler, 1995), its use by older adults will be observed only in difficult selection tasks.

Finally, studies of another variety of inhibition, referred to as "inhibition of return" (IOR), have consistently shown age-equivalent effects. If a target is preceded by a peripheral cue at the same location, the RT to the target is initially speeded. However, if the interval between the peripheral cue and the target is longer than 300–400 ms, the RT to the target is slower at the cued location than it is if the target occurs elsewhere in the visual field. This slowing of RT is referred to as IOR (Posner & Cohen, 1984). IOR has been viewed as reflecting a mechanism that ensures that a location in the visual field that has recently been inspected is not searched again, at least within a limited period of time. Interestingly, IOR occurs not only for manual responses but also for saccades (Rafal, Calabresi, Brennan, & Sciolto, 1989). Hartley and Kieley (1995; also see Faust & Balota, 1997) performed a series of studies to examine potential age-related differences in IOR. Across four separate studies, IOR was found to be at least as large for older as younger adults in both detection and discrimination tasks. Thus, it would appear that inhibition of spatial location, at least with regards to manual responding, is relatively insensitive to age.

In summary, the literature on aging and inhibition shows a mixed set of results with large and robust age-related deficiencies in the ability to inhibit a word while processing a color, equivocal results with regard to inhibitory processes involved in selecting a target from among distractors, and age equivalence in the inhibition of a recently attended location in visual space. However, these results do suggest two tentative conclusions: First, inhibition cannot be treated as a unitary construct. Second, inhibitory failures during aging appear to be specific rather than general.

Experiment 1

In this study, we used the paradigm illustrated in Figure 1 to examine potential age-related differences in attentional capture by task-irrelevant abrupt onsets (i.e., new objects). Subjects were instructed to maintain fixation in the center of the display until a color change on the peripheral circles defined the location of the color singleton target (i.e., the only circle that did not change color). At that point subjects were to move their eyes as quickly as possible to the color singleton target and to identify the small letter inside of the circle. On half the trials, an onset distractor, in the same color as the other distractor circles, appeared simultaneously with the color change that defined the location of the color singleton target. The onset distractor never served as the target.

Within this task we were particularly interested in potential age-related differences in attentional capture as reflected in both manual RT and oculomotor control. As indicated above, studies with younger adults have revealed both increases in RT with the appearance of a onset distractor (Remington et al., 1992; Theeu-

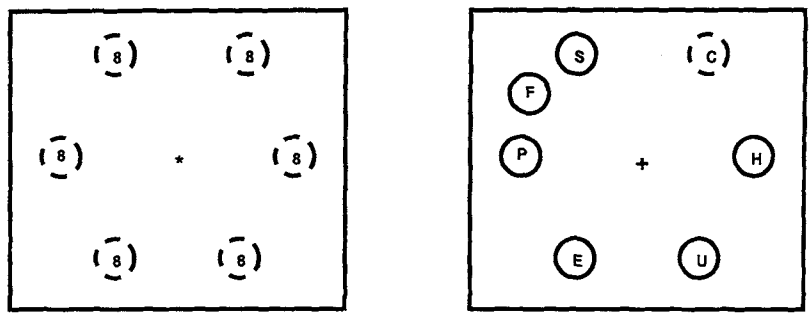


Figure 1. Graphic illustration of the temporal sequence of displays presented in Experiment 1. The gray circles are represented by dashed lines. The red circles are represented by solid lines.

wes, 1994) and misfixations on the onset distractor during visual search (Theeuwes, Kramer, Hahn, & Irwin, 1998). Given the literature on aging and inhibition, it is an open question as to whether older adults will have more difficulty inhibiting the effect of the onset distractor on the processing of the color singleton target, as reflected in manual RT and oculomotor control, than do younger adults. However, given the role of the prefrontal and frontal cortex in the inhibition of reflexive saccades (Guitton et al., 1985; Pierrot-Deselligny et al., 1995; Schall & Hanes, 1993), along with the often-reported observation that older adults fare more poorly on frontal tasks than do younger adults (West, 1996), it would appear likely that older adults would show a higher proportion of misfixations on the onset distractor than would younger adults.[1]

Method

Subjects. Eight older and eight younger adults participated in the study. The older adults ranged in age from 65 to 75 years (mean age = 69.5). Six of the older adults were women. The younger adults ranged in age from 18 to 28 years (mean age = 23.8). Five of the younger adults were women. All of the younger and older adults had near and far visual acuities at least 20/40, as measured by Snellen charts. All subjects also received a perfect score on the Ishihara Color Blindness Test. The mean number of years of education for the younger and older adults were 15.5 (range = 12–18) and 14.5 (range = 12–16 years), respectively. The subjects were paid $5 per hour for participation in the study.

Apparatus. A Gateway Pentium 133 MHz computer with a 19-in. (48.26-cm) supervideo graphics array color monitor was used to present the stimuli, control the timing of the experimental events, and record subjects RTs. Eye movements were recorded with an Eyelink tracker (SR Research, Toronto, Canada) with 250 Hz of temporal resolution and a 0.2° spatial resolution. The system uses an infrared video-based tracking technology to compute the center and size of the pupils in both eyes. An infrared head motion tracking system tracked head motion. Even though head motion was measured, the head was stabilized with a chin rest. The chin rest was located 53.3 cm from the monitor.

Stimuli. The observers viewed displays containing six equally spaced gray circles (3.7° in diameter), each containing a small gray figure eight premask (0.4° × 0.2°) presented on an imaginary circle with a radius of 12.6°. A 0.3° × 0.3° star was presented in the center of display and used for fixation. After 1,000 ms, all circles but one changed to red, and line segments were simultaneously removed from each of the figure eight premasks revealing target and distractor letters. At this time the fixation star also changed to a cross to inform the subjects that they should move their eyes to the color singleton circle. Their task was to determine whether the letter inside of the gray circle was either a *c* or a reversed *c*. The subjects responded by pressing the *z* or forward slash (\) key on the computer keyboard. The mapping of the response keys to the stimuli (i.e., *c* or reversed *c*) was counterbalanced across subjects. The letters inside the red circles were distractor letters randomly sampled without replacement from the set of *S, H, E, P, F,* and *U*. The red and gray circles were matched for luminance (24 cd/m^2). Because the letters were small the subjects had to make a saccade to the gray circle (i.e., the color singleton) to identify the target letter.

In addition to the six circles, in the onset condition an additional red circle (identical to the other five red circles) with a distractor letter inside was added to the display simultaneously with the color change that defined the singleton target. The additional red circle appeared with an abrupt onset at either of one of four possible locations (i.e., at either the 2, 4, 8, or 10 o'clock positions). These four possible locations where the onset could appear corresponded to three possible distances from the gray target circle. On the imaginary circle with the fixation point at its center, the abrupt onset was presented next to the target describing an angle between the target and distractor of 30°, three clock positions away from the target describing an angle of 90°, or five clock positions away from the target describing an angle of 150° arc. In euclidean distances, these figures corresponded to 6.4°, 19.4°, and 25.4° of visual angle, respectively. The stimuli remained presented until a response was made by the subject. Figure 1 shows an overview of the sequence of events in each of the trials.

Design. Observers participated in two different conditions that were randomly distributed within each block of trials. The first was an onset condition in which an abrupt-onset circle was added to the display simultaneously with the color change that defined the color singleton target. The abrupt onset was never the target. The second was a control condition in which only six circles (i.e., the gray target circle with the *c* or reversed *c*

[1] There is also substantial evidence to suggest that morphological and functional changes in brain activity do not occur uniformly during the process of normal aging. Researchers have reported substantially larger reductions in gray matter volume in association areas of the cortex, particularly in the prefrontal and frontal regions, than in sensory cortical regions (Coffey et al., 1992; Pefferbaum et al., 1992; Raz et al., 1994). Studies of functional brain activity using positron emission tomography have shown similar trends, with prefrontal regions showing substantially larger decreases in metabolic activity than sensory areas of the cortex (Azari et al., 1992; Salmon et al., 1991).

and the five red distractor circles with the response neutral letters) were present in the display.

Subjects performed one practice block of 64 trials and four experimental blocks with 64 trials per block, for a total of 256 experimental trials. Each block contained 32 control and 32 onset trials. Targets were presented randomly at each of the six equally spaced positions. On onset trials, abrupt-onset distractors were presented randomly at each of the three separations from the target.

Procedure. Before starting the experiment, the head band of the Eyelink tracker with the infrared light source and camera were strapped tightly on the subject's head. A chin rest was used to stabilize the head. Subjects were asked not to make any (large) head movements. The infrared source and the eye camera were adjusted until there was a clear corneal reflection in both eyes. After setting the threshold for detecting the pupil, we calibrated the Eyelink system. Subjects had to fixate nine calibration targets that were presented in a 3 × 3 grid in a random order across the monitor. As soon as a target was fixated, the next target appeared and the subject moved his or her eyes to fixate it. Once the calibration procedure was successfully completed, the experiment began.

Subjects served in one experimental session that lasted approximately 1 hr. Subjects were instructed that they should initially maintain their eyes on the fixation star. On each trial the eye position was automatically recalibrated to the center position so that reliable eye movement measurements could be obtained. After fixation, subjects were instructed to press the space bar on the computer keyboard to initiate the trial.[2] The display of six gray circles with figure eight premasks inside were then presented for 1,000 ms. Five of the circles then changed to red, and on onset trials an additional red circle was presented in the display. Subjects were instructed to move their eyes to the gray circle as soon as they detected the color change (and the change of the fixation star into a fixation cross) and to and make one response if they detected a *c* and another response if they detected a reversed *c*. The subjects were provided with feedback on their speed and accuracy of responding after each block of trials.

Results and Discussion

Discarded data. Data were discarded for several reasons. Trials were discarded if subjects moved their eyes from fixation before the color change that signaled the location of the target. This led to a loss of 7.2% of the trials for the younger adults and 18.8% of the trials for the older adults. Trials on which subjects made errors on their manual responses to the targets were also discarded. This led to a loss of 4.3% of the trials for the younger and 1.1% of the trials for the older adults. Finally, trials were discarded whenever the manual RT was less than 100 ms or greater than 5,000 ms. This led to a loss of 0.5% of the trials for the older and 0.05% of the trials for the younger adults.

Manual RT. The mean RTs to the singleton targets are presented in Table 1 for the younger and older adults in each of the experimental conditions. These data were submitted to a two-way analysis of variance (ANOVA) with age as a between-subjects factor and configuration (control, onset 30°, onset 90°, and onset 150°) as a within-subjects factor. Main effects were obtained for age, $F(1, 14) = 18.6$, $MsE = 3{,}655{,}348$, $p < .01$, and configuration, $F(3, 42) = 7.8$, $MsE = 13{,}166$, $p < .01$. RTs were faster for the younger than for the older adults. RTs were also faster for the control than for the onset conditions, which were not significantly different from each other.[3] The Age × Configuration interaction was not significant ($p > .70$).

Accuracies were uniformly high for all of the conditions and for the younger and older adults (i.e., accuracies exceeded 95% in all of the experimental conditions). Only the main effect of age was statistically significant, $F(1, 14) = 16.9$, $MsE = 0.0170$, $p < .01$. Older adults were more accurate in their identification of the target letters than were the younger adults (98.9% and 95.7% for the older and younger adults, respectively).

Table 1
Mean Reaction Times (in Milliseconds) for the Younger and Older Adults in Each Condition in Experiment 1

	Condition							
	Control		Onset 30		Onset 90		Onset 150	
Group	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Younger	771	41	838	48	842	56	842	51
Older	1,268	88	1,316	103	1,312	92	1,310	104

Note. The Onset 30, Onset 90, and Onset 150 labels indicate the conditions in which the onset distractor appeared 30°, 90°, and 150° from the color singleton target (measured from fixation), respectively.

These data are consistent with previous reports of disruption of performance by a task-irrelevant singleton (Shepherd et al., 1986; Theeuwes, 1994, 1995). Interestingly, the magnitude of the attention capture effect was equivalent for the younger and the older adults, suggesting that the older adults are as efficient at inhibiting a task-irrelevant onset as are the younger adults.

An additional analysis was performed to examine the influence of initial scan path on RTs. Consistent with our research with younger adults (Theeuwes, Kramer, Hahn, & Irwin, 1998), both younger and older adults misfixated the onset distractor on a substantial number of trials (see the section on scan path) before fixating on the color singleton. Given that the color singleton target could be identified only when it was fixated (because of its small size), it is of interest to determine the extent of the RT increase that is incurred when their eyes first go to the onset distractor before arriving at the color singleton target.

To that end, we sorted the RTs on the basis of whether the eyes first went to the onset or instead directly to the color singleton target. These data were submitted to a three-way ANOVA with age as a between-subjects factor and configuration (onset 90° and onset 150° separation from the target) and path (directly to the target or initially to the onset)[4] as within-subjects factors. Main effects were obtained for age, $F(1, 14) = 20.1$, $MsE = 3{,}380{,}823$, $p < .01$, and path, $F(1, 14) = 120.9$, $MsE = 567{,}103$, $p < .01$. The older adults were slower than the younger adults. RTs on trials on which the eyes went directly to the color singleton target were

[2] A computer algorithm ensured that a trial could not begin unless an observer's eyes were fixated within 1.5° of the fixation point.

[3] All post hoc comparisons were performed with Bonferroni *t* tests and are significant at the .05 level.

[4] Saccade paths to the onset were defined as eye movements that moved from fixation to within 15° toward the left or the right of the onset (i.e., within a 30° cone that extended from fixation to the onset, centered on the onset). The same ±15° criterion was used to define saccades to the color singleton target. We used the data only from the 90° and 150° conditions (i.e., the separation between the color singleton target and the onset distractor) because the definition of scan path was unambiguous in these two conditions.

faster than trials on which the eyes first went to the onset distractor before going to the singleton target. Finally, there was a significant interaction between age and path, $F(1, 14) = 5.1$, $MsE = 23{,}810$, $p < .05$. The mean RTs for trials on which the eyes went directly to the target and trials on which the eyes first went to the onset distractors were 777 and 927 ms for the younger adults and 1,199 and 1,425 ms for the older adults. A potential explanation for the larger difference in RTs between these conditions for the older than for the younger adults is examined in the section on saccade accuracy.

Saccade path. Three thresholds were used for saccade detection: movement distance, velocity, and acceleration. An eye movement was considered a saccade either when the movement distance exceeded 0.2° and velocity exceeded 30 deg/s, or when the movement distance exceeded 0.2° and the acceleration exceeded 8,000 deg/s^2.

Figure 2 shows the initial scan paths for the younger and older adults in the control condition and each of the three onset conditions. The stimulus arrangements have been rotated across trials to align color singleton target locations (indicated by the darker circle) and the onset distractor locations at the 30°, 90°, and 150° separations. Figure 3 shows a different view of these data by providing the distributions of the angular deviation of the initial saccade from the center of the color singleton target. As can be seen from the figures, subjects' initial saccades in the control condition (i.e., the condition without the task-irrelevant onset distractor) generally moved directly toward the color singleton target. However, a much different pattern of saccades was present when the onset appeared in the display. In this case, a fairly substantial number of saccades initially went toward the onset distractor (which appeared at the 10, 2, and 4 o'clock positions for the 30°, 90°, and 150° onset trials, respectively) before stopping briefly and continuing on to the color singleton target.

We quantified these observations by calculating the percentage of trials on which the eyes went initially toward the onset. These data were then submitted to a two-way ANOVA with age as a between-subjects factor and configuration (onset at 90° and 150° from the target) as a within-subjects factor. Neither the main effect of age or configuration nor the interaction between these two factors was statistically significant ($ps > .21$). The percentage of trials on which the eyes went directly toward the onset distractor were 44% and 42% for the 90° and 150° onset conditions for the younger adults. The comparable data for the older adults were 46% and 48%. Thus, these data are consistent with the RT data in suggesting that older adults are as capable (or incapable, depending on one's perspective) as younger adults in overriding attentional capture by the task-irrelevant distractor.[5] Furthermore, the data argue that age equivalence in attentional capture effects is similar for performance measures such as RT and accuracy and at least one measure of oculomotor control, that is, the ability to prevent misfixatations on the onset distractor. We turn now to the analysis of temporal measures of oculomotor control to further examine age effects.

Fixation duration after a saccade to the onset distractor. In previous research we found that fixations that occurred between an initial saccade to the onset distractor and the subsequent movement of the eyes to the color singleton target were brief (Theeuwes, Kramer, Hahn, & Irwin, 1998). In fact, fixation durations were too brief to enable the programming of another eye movement. These data led us to suggest that two saccades were programmed in parallel, a reflexive saccade to the onset and a goal-directed saccade to the color singleton target. In this case, full reprogramming of a saccade from the location of the onset distractor to the target would not be necessary and therefore fixation durations would be brief.

The distribution of fixation durations for those trials on which the eyes went initially to the onset distractor are presented in Figure 4 for the younger and older adults. As can be seen in the figure, the great majority of the fixations were too brief to enable the programming of another saccade to the target (which typically takes 150 ms; see Becker, 1991; Findlay, 1997; Salthouse & Ellis, 1980). Therefore, it would appear that both younger and older adults are capable of programming two eye movements in parallel (Becker & Jurgens, 1979; Henderson & Ferreira, 1990; Reichle, Pollatsek, Fisher, & Rayner, 1998). Indeed, the difference in mean fixation duration between the younger and older adults was not statistically significant ($p > .55$; younger and older adults mean fixation durations were 106 and 122 ms, respectively).

Assuming that the goal-directed and reflexive eye movements are indeed programmed in parallel, the question remains as to why there is any, however brief, time required between the saccade to the onset distractor and the subsequent saccade to the target. Although the present data cannot answer this question with any degree of certainty, there would appear to be at least two possibilities. First, it would appear conceivable that some finite amount of time is required to inhibit the processing of the onset before the oculomotor system can be released to redirect the eyes to the target. Second, time may be required for reprogramming of the saccade to the target for those components of the oculomotor system that use a retinotopic coordinate system (i.e., a coordinate system in which the target location is determined with respect to the position of the eye). Indeed, the frontal eye fields, a cortical area involved in the programming of goal-directed saccades, does use a retinotopic coordinate system (Schall & Hanes, 1993; Schlag & Schlag-Rey, 1990). However, other components of the oculomotor system (e.g., supplementary eye fields) appear to be capable of programming and directing saccades within craniotopic coordinates (i.e., a coordinate system in which the target location is determined with respect to the position of the head and therefore the eye is programmed to reach a specific position in the orbit) and therefore would not require that the saccade to the target be reprogrammed after the eyes land near the onset distractor (Mays & Sparks, 1980; Pierrot-Deseilligny et al., 1995; Zee et al., 1976). In any event, the inhibition and reprogramming hypotheses, which are not mutually exclusive, are potential explanations for the brief fixation durations that need to be further examined in future research.

Saccadic latency. Saccade latency was defined as the time that

[5] Power analyses indicated that at an alpha of .05, there was a greater than .32 probability to detect an f of greater than .40 for the age comparison. Although this indicates a fairly low power to detect a significant age difference in the proportion of misfixations on the onset distractor when the data from Experiments 1 and 2 were combined, the power increases to .60 (Cohen, 1988). In any event, the important point is that age differences in the proportion of misfixations on the onset distractor are extremely small compared with those observed in the antisaccade task (Olincy, Ross, Young, & Freedman, 1997).

it took the eyes to start moving from the center fixation dot to the color singleton target or onset distractor. The timing began with the color change that defined the location of the target and ended as soon as the eyes moved away from fixation (i.e., a 2° circular area around the center fixation dot).

These data were submitted to a three-way ANOVA with age as a between-subjects factor and path (saccade directly to the target or initially to the onset distractor) and configuration (onset at a 90° or 150° separation from the target) as within-subjects factors. As expected (Huaman & Sharpe, 1993; Moschner & Baloh, 1994; Whitaker, Shoptaugh, & Haywood, 1986), older adults took longer to move their eyes away from fixation than did younger adults, $F(1, 14) = 20.1$, $MsE = 220{,}156$, $p < .01$; the mean RTs for the older and the younger adults were 353 ms ($SD = 72$) and 235 ms ($SD = 41$), respectively. There was also a significant main effect for path, $F(1, 14) = 18.1$, $MsE = 26{,}486$, $p < .01$. Saccadic latencies were shorter for trials on which the eyes initially moved to the onset distractor ($M = 274$ ms, $SD = 73$) than for trials on which the eyes went directly to the target ($M = 315$ ms, $SD = 88$). Thus, these data suggest that fast eye movements reflect cases in which captured (involuntary) saccades won the race with voluntary saccades. None of the other main effects or interactions was significant.

The magnitude of the difference in saccadic latency between the eye movements that went directly to the target and those that first went to the onset distractor was statistically equivalent for younger and older adults. For younger adults, the saccadic latency for trials that went directly to the target was 251 ms compared with 221 ms for trials than first went to the onset distractor. The comparable latencies for the older adults were 379 and 327 ms. Thus, these data are consistent with our speculation that it takes some finite amount of time to override or inhibit attentional capture by the appearance of a task-irrelevant abrupt onset. Eye movements that are emitted before the imposition of inhibition of the onset are misdirected to the location of the onset before being released and redirected to the target.

Saccade accuracy. The RT data discussed above (see the section on manual RT) indicated that there was a significantly larger performance cost for older adults than for younger adults for trials on which the eyes first went to the onset distractor than for trials on which the eyes went directly to the color singleton target (150 and 226 ms for the younger and older adults, respectively). An important question concerns the nature of this differential RT cost.

One possibility that can quickly be discounted concerns saccadic latency. Although older adults did take longer to begin to move their eyes away from fixation than younger adults, this difference in saccadic latency is not relevant to our finding of a differential RT cost because fixation durations after a saccade to the onset distractor were statistically equivalent for younger and older adults (the average fixation duration was 106 and 122 ms for the younger and older adults, respectively). Thus, after a brief fixation near the onset distractor, both younger and older adults were able to rapidly begin to move their eyes toward the color singleton target.

The amount of time required to move the eyes between fixation and the onset (i.e., saccade duration) and again between the onset and the color singleton target may have contributed in part to the larger RT difference for the older than for the younger adults for those trials on which the eyes first went to the onset than for those trials on which the subjects' eyes went directly to the target. We examined this issue by computing the mean saccade durations and submitting these data to a two-way ANOVA with age as a between subjects factor and configuration (control, onset 30°, onset 90°, and onset 150°) as a within subjects factor. Neither the main effects not the interactions were significant ($ps > .7$). The mean saccade duration for both the younger and older adults was 48 ms. Therefore, the speed with which subjects moved their eyes could not account for the RT difference between the younger and older adults.

One remaining hypothesis that we examined concerned the accuracy of subjects' saccades on trials on which their eyes first went to the onset distractor. On these trials younger adults made an average of 1.3 saccades to move their eyes from the onset distractor to the color singleton target (i.e., to come within 2° of the color singleton target). The comparable figure for the older adults was 1.8 saccades. The number of saccades to reach the target, after having first fixated the onset distractor, was significantly larger for the older than for the younger adults, $F(1, 14) = 5.8$, $MsE = 29.07$, $p < .05$. Therefore, it would appear that the larger RT difference (76 ms) for the older than for the younger adults for trials on which the eyes first went to the onset as compared with trials on which the eyes went directly to the target can be attributed to the age-related difference in saccade accuracy. That is, older adults made more saccades to reach the target than did younger adults. This finding is consistent with other reports of decreases in saccadic accuracy with age (Huaman & Sharpe, 1993).

Experiment 2

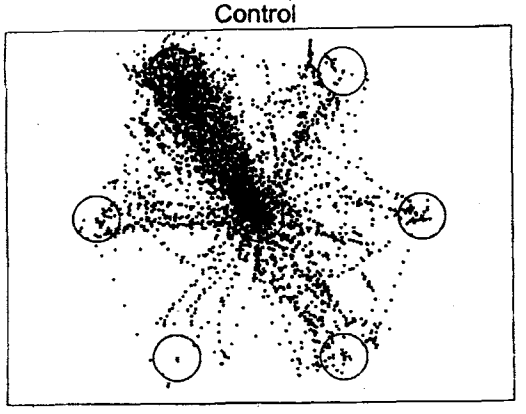
The performance and eye movement results obtained in Experiment 1 suggest that the capture of attention by task-irrelevant onsets is relatively age invariant. The magnitude of RT slowing engendered by the appearance of an onset was equivalent for younger and older adults, as were the proportion of trials on which the eyes were misdirected to the onsets. The younger and older adults were also equally capable of a rapid redirection of the eyes to the color singleton target after misfixations on the onset distractor. These data suggest parallel programming of the two eye movements, a reflexive eye movement to the onset and a goal-directed saccade to the target, for both younger and older adults. Finally, for both younger and older adults, rapid eye movements away from fixation were more susceptible to capture than were slower eye movements.

In general, these data suggest a sparing of inhibitory processes during the course of normal aging, a finding consistent with the spared inhibition observed in the IOR paradigm and in a subset of the negative priming studies (Faust & Balota, 1997; Hartley & Kiely, 1995; Kramer et al., 1994; Sullivan et al., 1995). More specifically, the inhibitory processes examined in the present studies presumably involve the inhibition of a covert shift of attention and an overt shift of the eyes to the location of the task-irrelevant abrupt-onset object. In fact, there is abundant evidence that suggests that the inhibition of a reflexive saccade to the onset requires efficient functioning of the frontal eye movement system that includes some subset of the frontal eye fields, supplementary eye fields, and the dorsolateral prefrontal cortex (Guitton et al., 1985; Rivaud, Muri, Gaymard, Vermersch, & Pierrot-Deseilligny, 1994;

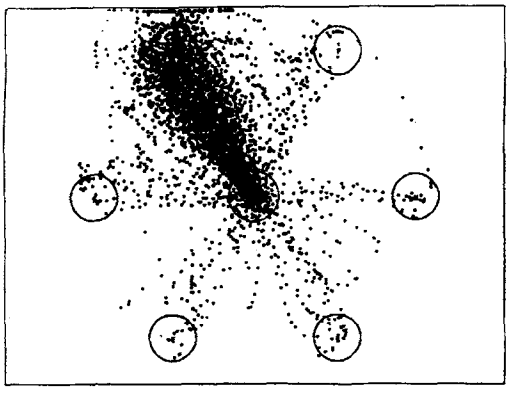
OLD

YOUNG

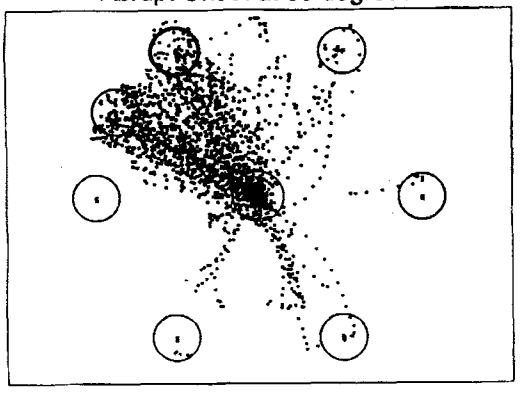
Control



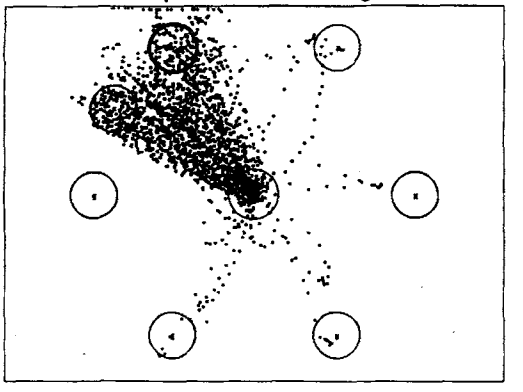
Control



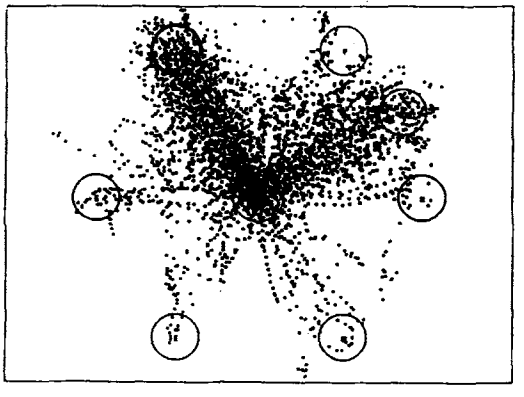
Abrupt Onset at 30 degrees



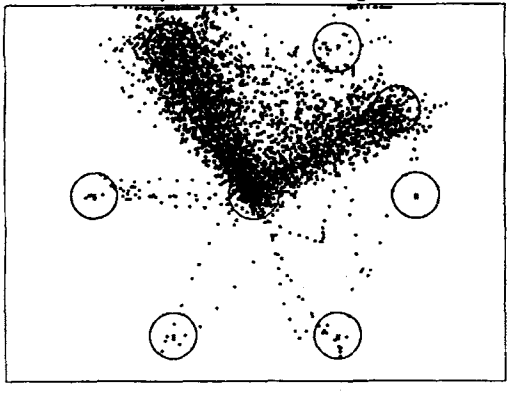
Abrupt Onset at 30 degrees



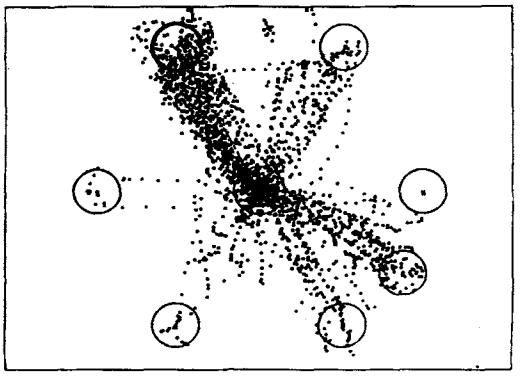
Abrupt Onset at 90 degrees



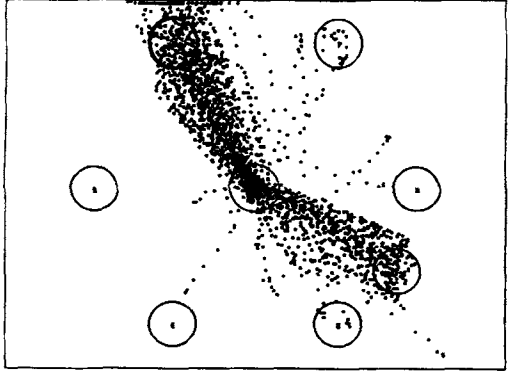
Abrupt Onset at 90 degrees



Abrupt Onset at 150 degrees



Abrupt Onset at 150 degrees



Schlag-Rey, Amador, Sanchez, & Schlag, 1997). Therefore, the present data appear to suggest age-related sparing of a task that relies on processing in frontal cortex, an observation not generally reported in the literature (but see Kramer, Hahn, & Gopher, in press).

Although the data obtained in Experiment 1 do suggest age invariance of the processes that underlie the phenomenon of attentional and oculomotor capture, there are some alternative interpretations of our results. First, it is conceivable that the age equivalence observed for the pattern of RT slowing and proportion of misfixations on the onset distractor is the result of decreased peripheral acuity or restricted attentional field for the older adults. Indeed, there is now substantial evidence that suggests that older adults have more difficulty performing a task at fovea while simultaneously detecting a target in the periphery than do younger adults (Ball, Beard, Roenker, Miller, & Griggs, 1988; Owsley, Ball, Sloane, Roenker, & Bruni, 1991). On the other hand, studies also suggest age equivalence of attentional breadth in tasks that require the detection of a singleton target, as was the case in the present study (Humphrey & Kramer, 1997; Plude & Doussard-Roosevelt, 1989). In addition, the high accuracy rate achieved by both younger and older adults would suggest that the older adults were highly capable of detecting peripheral change in our feature detection paradigm. In any event, we decided to further examine this issue in the present study by decreasing by 32% the diameter of the circle on which the target and distractors were presented. If the age equivalence in attentional capture observed in Experiment 1 was the result of decreased acuity or attentional breadth for the older adults, we would expect to observe larger increases in RTs and a greater number of misfixations to the onset for the older than for the younger adults in the present study.

We also made another change in the present study that may explain in part the age equivalence in attention capture effects observed in Experiment 1. In the previous study, the onset and control trials differed both in terms of the presence or absence of an onset and also in terms of the number of stimuli on the display. That is, there was one additional object on the onset trials than on the control trials. This additional object could have reduced the visibility of the onset, thereby reducing any potential age effects between the onset and control trials. It was also the case, as illustrated in Figure 1, that there was the potential for differential grouping of the distractors on the onset and control trials in Experiment 1 because the proximity between the onset and the two adjoining distractors was less than the proximity between any of the other distractors. However, the proximity between all of the distractors was equivalent on the control trials in Experiment 1 because there was one fewer distractor (i.e., the onset distractor) on these trials. To alleviate these potential problems, we equated the number of objects on the control and onset trials in this study.

Method

Subjects. Eight older and eight younger adults participated in the study. The older adults ranged in age from 65 to 75 years (mean age = 67.8). Four of the older adults were women. The younger adults ranged in age from 19 to 26 years (mean age = 21.6). Seven of the younger adults were women. All the younger and older adults had near and far visual acuities at least 20/40, as measured by Snellen charts. All subjects also received a perfect score on the Ishihara Color Blindness Test. The mean number of years of education for the younger and older adults were 15.2 (range = 13–17) and 15.8 (range = 12–20), respectively. The subjects were paid $5 per hour for their participation in the study.

Apparatus. The apparatus was the same as that used in Experiment 1.

Stimuli. The stimuli were the same as those used in the previous experiment, with three exceptions. First, the number of stimuli on control and onset trials was now equivalent. That is, an extra circle with a figure eight premask (which turned into a distractor letter) was now presented on the control trials. This was done to ensure that any RT or eye movement differences between control and onset trials were due to the appearance of the abrupt onset rather than to a different number of stimuli in the two conditions. Second, the radius of the imaginary circle on which the stimuli were presented was reduced from 12.6° in Experiment 1 to 8.6° in the present study. The euclidean distances between the target and onset distractor (or extra control stimulus) were 13.6° and 17.8° of visual angle. Finally, the onset distractor (and the nononset distractor on the control trials) could appear either 90° or 150° from the color singleton target. The 30° separation between the color singleton target and the onset–control distractor was eliminated in this study because of the difficulty of distinguishing between initial saccades to the target versus the distractor at the close separation in Experiment 1.

Design. The design and number of practice and experimental trials were the same as those used in Experiment 1, with the following exception. Only two color singleton–onset distractor separations were used in the present study, 90° and 150° separations.

Procedure. The procedure was the same as that used in Experiment 1.

Results and Discussion

Discarded data. Data were discarded for various reasons. Trials were discarded if subjects moved their eyes from fixation before the color change that signaled the location of the target. This led to a loss of 10.2% of the trials for the younger adults and 13.1% of the trials for the older adults. Trials on which subjects made errors on their manual responses to the targets were also discarded. This led to a loss of 0.3% of the trials for the younger and 0.4% of the trials for the older adults. Finally, trials were discarded whenever the manual RT was less than 100 ms or greater than 5,000 ms. This led to a loss of 0.2% of the trials for the older and 0.1% of the trials for the younger adults.

Manual RT. The mean RTs to the singleton targets are presented in Table 2 for the younger and older adults in each of the experimental conditions. These data were submitted to a three-way ANOVA with age as a between-subjects factor and configuration (onset and control) and target–distractor distance (90° and 150°) as within-subjects factors. Main effects were obtained for age, $F(1,$

Figure 2. An illustration of the scan path of the initial saccade for the control and the three onset conditions (i.e., target–onset distractor separation of 30°, 90°, and 150°) for all observers in Experiment 1. Each of the points represents an *x–y* position digitizer value at a digitizing rate of 250 Hz. The plot includes the initial saccade paths for all the trials for each of the observers in the study. The plots are normalized such that all of the 30° separation trials are aligned on the single position represented in the figure. The same is true for the 90° and 150° color singleton–onset distractor separations.

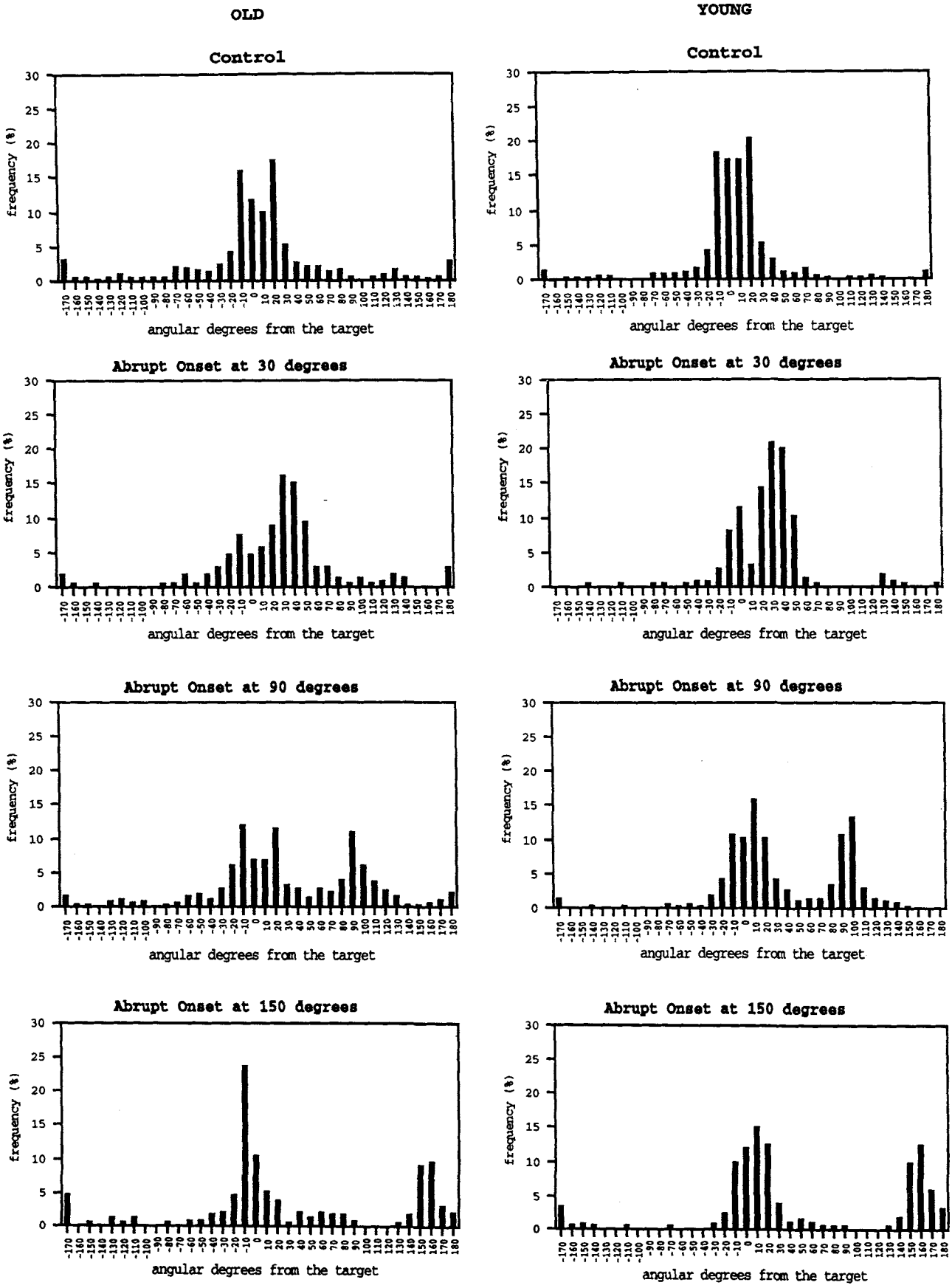


Figure 3. Histograms for the control and each of the three onset conditions that illustrate the maximal angular deviation from a straight line path from fixation to the position of the target on each of the initial saccades in Experiment 1. These data represent all the initial saccades for each of the observers in the study.

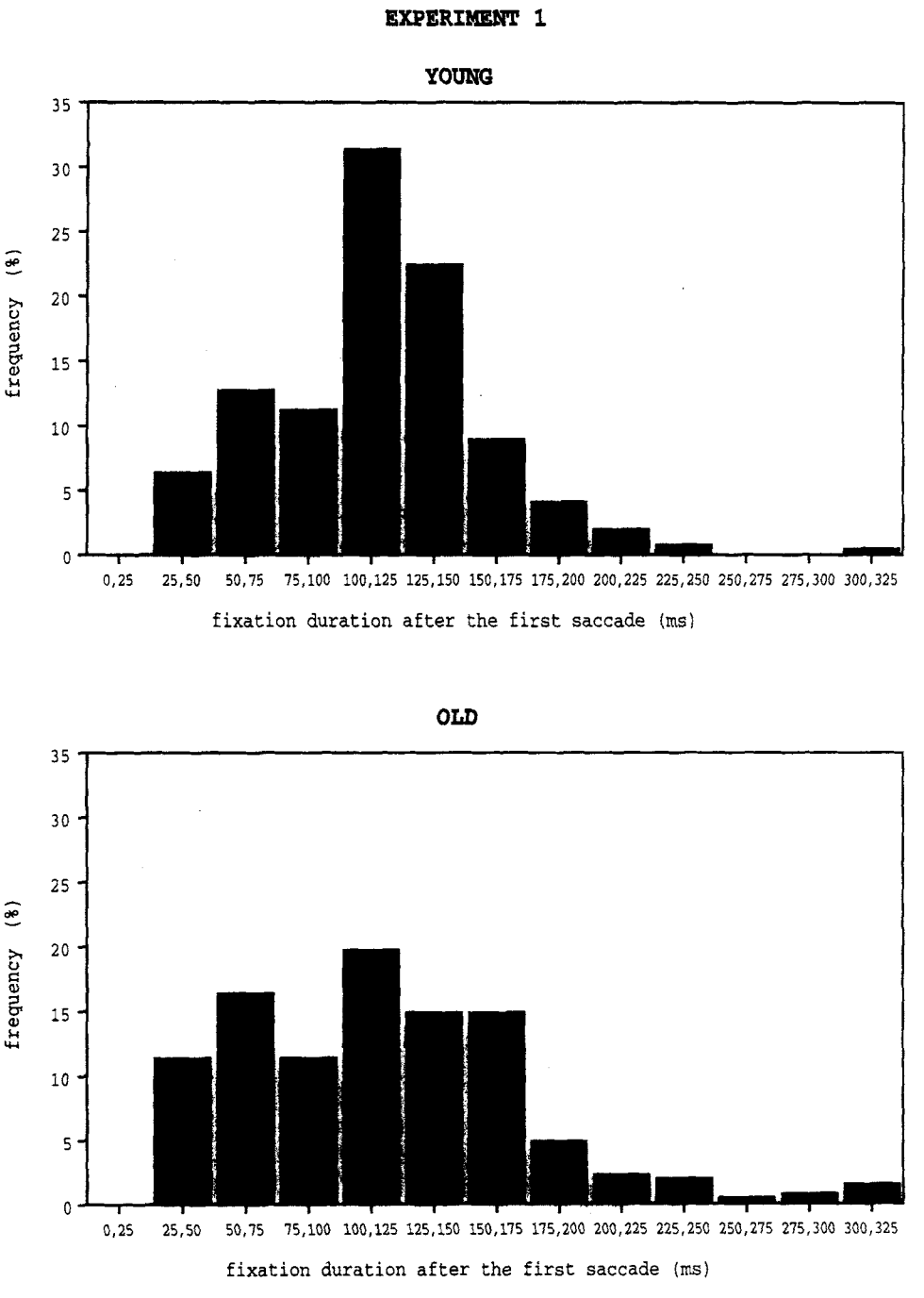


Figure 4. Fixation durations (in milliseconds) after the first saccade for those saccades that went toward the onset distractor. The results displayed here are from conditions in which the abrupt onset appeared at 90° and 150° from the target in Experiment 1.

14) = 14.7, MsE = 1,436,268, $p < .01$, and configuration, $F(1, 14)$ = 58.0, MsE = 17,084, $p < .01$. Older adults responded more slowly than did younger adults. RTs were faster on the control than on the onset trials.

As in Experiment 1, accuracies were uniformly high in all of the conditions for the younger and older adults (i.e., accuracies exceeded 97% across all of the experimental conditions for the younger and older adults). There were no significant main effects or interactions for the accuracy data.

We also contrasted the manual RTs on those trials on which the eyes went directly to the color singleton target with those on which the eyes first went to the onset distractor before continuing on to

Table 2
Mean Reaction Times (in Milliseconds) for the Younger and Older Adults in Each Condition in Experiment 2

	Condition							
	Control 90		Control 150		Onset 90		Onset 150	
Group	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
Younger	842	49	843	53	896	44	887	46
Older	1,184	54	1,207	61	1,236	58	1,249	56

the target. The RT data were submitted to a three-way ANOVA with age as a between-subjects factor and path (eyes directly to the target or initially to the onset) and configuration (onset 90° and onset 150° separation from the target) as within-subjects factors. Main effects were obtained for age, $F(1, 14) = 18.6$, $MsE = 2{,}034{,}825$, $p < .01$, and path, $F(1, 14) = 23.3$, $MsE = 331{,}685$, $p < .01$. Older adults responded more slowly than did younger adults. RTs were faster when the eyes went directly to the color singleton target (1,007 ms) than when they first went to the onset distractor (1,151 ms). As in Experiment 1, the difference in RTs between these two conditions was larger for older (1,161 vs. 1,352 ms) than for the younger (851 vs. 949 ms) adults. However, the Age × Path interaction was not significant ($p > .14$) in this study.

Although the interaction between path and age was not significant, as it was in Experiment 1, the difference in RTs between the levels of the path variable was 93 ms larger for the older than for the younger adults. Given the magnitude of this effect, we decided to examine whether this age-related difference in RT cost could be attributed to the number of saccades needed to reach the target on those trials on which the eyes first went to the onset distractor. The mean number of saccades needed to reach the target were 1.3 and 1.9 for the younger and older adults, respectively, $F(1, 14) = 9.6$, $MsE = 9.08$, $p < .01$. Therefore, as in the first study, older adults required more saccades, on average, to reach the color singleton target after having first fixated the onset distractor than did younger adults.

In summary, despite changes in the eccentricity of the stimulus array and the addition of the control trials in the present study, younger and older adults continued to display a similar pattern of manual RTs in response to the presence of a task-irrelevant abrupt onset. Thus, these data when viewed in terms of the pattern of RTs obtained in the first study strengthen our conclusion that the processes that underlie the phenomenon of attentional capture are age invariant.

Saccade path. Figure 5 shows the initial scan paths for the younger and older adults in the control and onset conditions. The stimulus arrangements have been rotated across trials to align color singleton target locations (indicated by the darker circle) and onset distractor locations at 90° and 150° separations. Figure 6 shows a different view of these data by providing the distributions of the angular deviation of the initial saccade from the center of the color singleton target. Consistent with the pattern of saccades observed in Experiment 1, the initial saccades in the control conditions generally moved in the direction of the color singleton target. However, a much different pattern of saccades was evident for the onset trials for both the younger and older adults. Like in Experiment 1, a substantial number of initial saccades were directed to the task-irrelevant abrupt onsets.

We quantified these observations by calculating the percentage of trials on which the eyes went initially toward the onset. These data were then submitted to a three-way ANOVA with age as a between-subjects factor and configuration (onset and control) and target–distractor distance (90° and 150°) as within-subjects factors. Only the main effect of configuration was significant, $F(1, 14) = 40.1$, $MsE = 238.1$, $p < .01$. A higher percentage of saccades went to the 90° and 150° distractors on the onset than on the control trials (42% vs. 13%, respectively). Indeed, as in Experiment 1, the percentage of trials on which the eyes first went to the onset was similar for the younger and older adults (40% and 43% for the younger and older adults, respectively). Thus, it appears that moving the task-irrelevant onset distractor 32% closer to fixation had no effect on the percentage of trials on which either the younger or older adults misfixated the onsets.

Fixation duration after a saccade to the onset distractor. The distribution of fixation durations for those trials on which the eyes went initially to the onset distractor are presented in Figure 7 for the younger and older adults. Consistent with the data obtained in the first study, fixation durations were brief for a large subset of trials for both the younger and older adults. The mean fixation durations were submitted to a two-way ANOVA with age as a between-subjects factor and target–onset distance as a within-subjects factor. Neither the main effects nor the interaction was significant. The mean fixation durations for the younger and older adults on the trials on which the eyes initially went to the onset were 108 and 129 ms, respectively. Thus, these data, like the data obtained in Experiment 1, suggest that both younger and older adults are capable of programming two eye movements, a reflexive eye movements toward the onset distractor and goal-directed eye movement to the target, in parallel (Becker & Jurgens, 1979; Henderson & Ferreira, 1990; Reichle et al., 1998).

Saccade latency. The average saccade latencies were submitted to a three-way ANOVA with age as a between-subjects factor and path (saccade directly to the target or initially to the onset distractor) and target–distractor distance (90° and 150°) as within-subjects factors. Main effects were obtained for age, $F(1, 14) = 12.4$, $MsE = 146{,}025$, $p < .010$, and path, $F(1, 14) = 35.2$, $MsE = 96.723$, $p < .01$. Older adults were slower at moving their eyes away from fixation than were younger adults (366 and 270 ms, respectively). Saccade latencies were shorter when subjects moved their eyes initially to the onset than when they moved their eyes directly to the color singleton target (279 and 358 ms, respectively).

General Discussion

The present studies were conducted to examine the influence of attentional capture[6] (see p. 150 for Footnote 6) by task-irrelevant abrupt onsets on the performance and oculomotor control of younger and older adults. Consistent with previous behavioral research with younger adults (Jonides, 1981; Remington et al., 1992; Theeuwes, 1994, 1995), search performance was disrupted, as evidenced by increased manual RTs, whenever an onset appeared in the display. Indeed, this disruption of performance occurred regardless of whether the task-irrelevant onset appeared

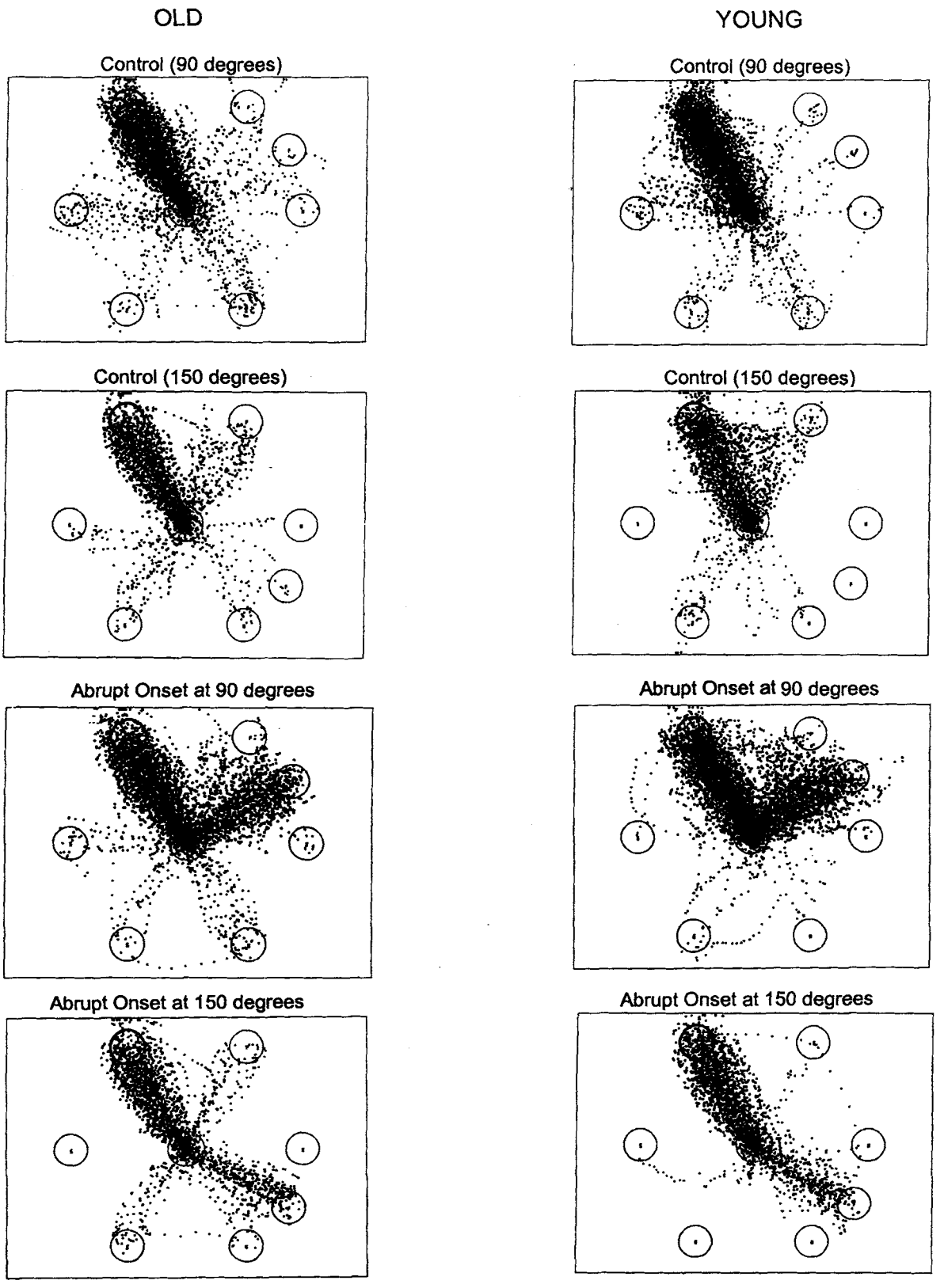


Figure 5. An illustration of the scan path of the initial saccade for the control and the two onset conditions (i.e., target–onset distractor separation of 90° and 150°) for all observers in Experiment 2. Each of the points represents an x–y position digitizer value at a digitizing rate of 250 Hz. The plot includes the initial saccade paths for all the trials for the onset and control conditions for each of the observers in the study.

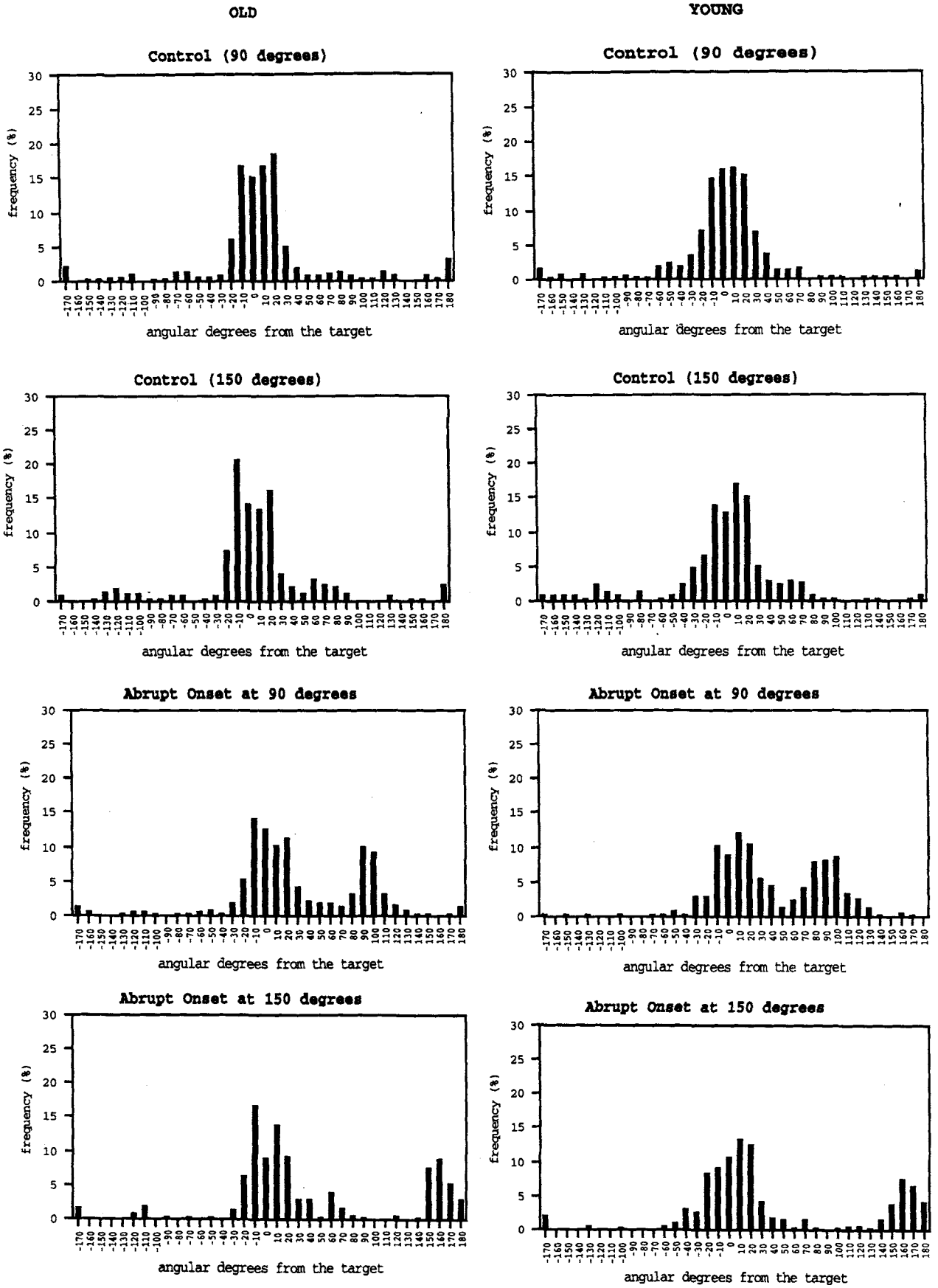


Figure 6. Histograms for the control and each of the two onset and control conditions that illustrate the maximal angular deviation from a straight line path from fixation to the position of the target on each of the initial saccades in Experiment 2. These data represent all the initial saccades for each of the observers in the study.

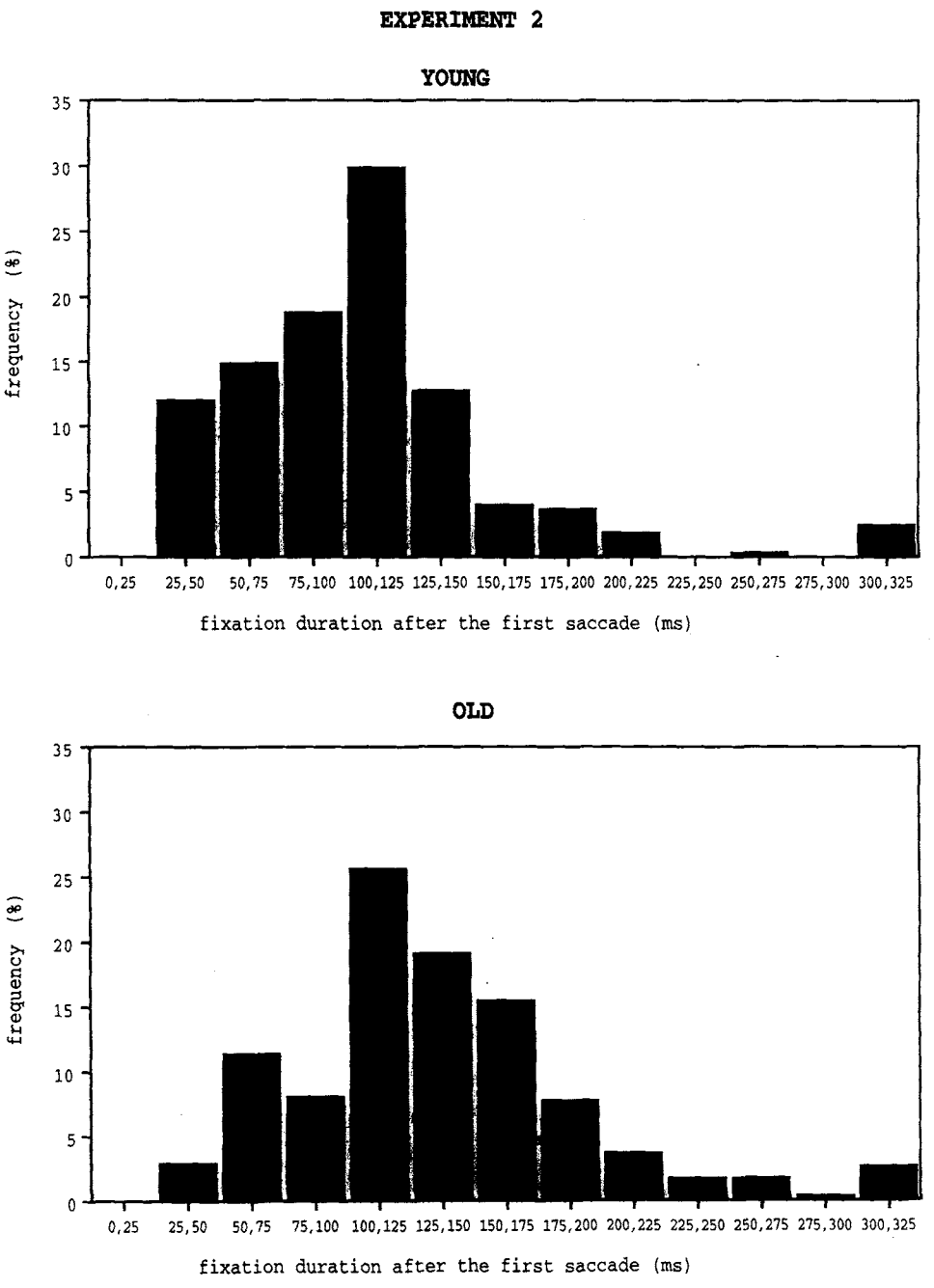


Figure 7. Fixation durations (in milliseconds) after the first saccade for those saccades that went toward the onset distractor. The results displayed here are from conditions in which the abrupt onset appeared at 90° and 150° from the target in Experiment 2.

close to the color singleton target or on the other side of the display. Furthermore, it is clear that the disruption of performance was a result of the appearance of the abrupt onset and not the presence of an additional object in the display.

Interestingly, younger and older adults showed statistically equivalent increases in search RTs with the appearance of a task-irrelevant object. These data suggest that the ability to inhibit the influence of task-irrelevant objects on search performance is maintained during the course of aging. Thus, these findings, along with results obtained in the IOR paradigm (Faust & Balota, 1997; Hartley & Kieley, 1995), argue for an age-related sparing of inhibitory processes that are directed to objects in visual space. However, as indicated above, it might be argued that our failure to find age-related differences in the disruption of performance is the result of decreased acuity or a decrease in the breadth of the attentional window or useful field of view (Ball et al., 1988;

Owsley et al., 1991) that is used to monitor for the color change that defines the location of the target. The results of Experiment 2 argue against such an alternative interpretation of our results. In Experiment 2 we moved the stimuli 32% closer to fixation than was the case in Experiment 1 and still failed to observe any change in the pattern of results. These results, along with the highly accurate performance exhibited by all the subjects in our two studies and previous reports of age-equivalent attentional fields in feature search tasks (Humphrey & Kramer, 1997; Plude & Doussard-Roosevelt, 1989), make it highly unlikely that our observation of similar performance effects for younger and older adults can be explained by a difference in the size of the attentional window.

In general, the influence of the appearance of a task-irrelevant object also had a similar effect on oculomotor control for younger and older adults. For both groups of subjects, the appearance of an onset resulted in (a) a large percentage of trials on which subjects moved their eyes to the onset before fixating the color singleton target, (b) brief fixations between the end of the saccade to the onset and the movement of the eyes to the target, and (c) faster saccade latencies for trials on which the eyes were misdirected to the onset than on trials on which the eyes went directly to the target. The only differences in oculomotor control exhibited by the two groups of subjects were in the speed with which the younger and older adults were able to begin to move their eyes away from fixation and in the number of saccades necessary to fixate the target after having first misfixated the onset distractor. This latter effect did have implications for age-related differences in performance in that older adults RTs were more adversely influenced than younger adults RTs on trials on which the eyes were misdirected to the onset distractor before fixating the target. However, the larger performance cost for the older adults on these trials likely reflects a general decrease in saccade accuracy with age rather than an age-related deficiency in the processes subserving attentional and oculomotor capture. This conclusion is supported by our finding of poorer saccade accuracy for older than for younger adults even on control trials (i.e., on trials on which an abrupt onset was not present to capture attention or the eyes). Older adults made more saccades to reach the color singleton target on control trials than did younger adults in both Experiment 1, $F(1, 14) = 5.0$, $MsE = 22.14$, $p < .05$ (1.5 and 1.2 saccades for the older and younger adults, respectively), and in Experiment 2, $F(1, 14) = 12.7$, $MsE = 19.81$, $p < .01$ (1.9 and 1.6 saccades for the older and younger adults, respectively).

Another interesting finding was that the duration of the fixations that occurred between the end of the saccade to the onset and the beginning of the subsequent eye movement to the target were statistically equivalent for younger and older adults (107 and 126 ms for the younger and older adults averaged across the two studies). Perhaps even more interesting, however, is that the majority of fixations observed in the two studies (see the fixation duration distributions in Figures 4 and 7) are generally acknowledged to be too brief to enable the programming of a saccade to the color singleton target (Becker, 1991; Findlay, 1997; Salthouse & Ellis, 1980). Therefore, it would appear that both younger and older adults were able to program the reflexive saccade to the onset and the goal-directed saccade to the target in parallel and to release the saccade to the target after only a brief fixation on the onset.

One interesting aspect of the data that we have not yet discussed was the subjects' level of awareness of the presence of the abrupt onset and if aware of the onset's presence their knowledge of whether they fixated it or not. In a previous study with younger adults (Theeuwes, Kramer, Hahn, & Irwin, 1998), it became apparent to us, on the basis of comments by the subjects and our informal questioning of them concerning the stimulus display, that subjects were generally unaware of the presence of the onset distractor and if they were aware of its presence they were insistent that they had never fixated on it. As a result of this information, we decided to collect subjective report data in the present research concerning the subjects' awareness of the presence of the abrupt onset distractor and their eye movements. Subjects were asked, at the conclusion of each experiment, to describe the displays and to report whether they had noticed anything out of the ordinary on any of the trials. Subjects were also asked how often they had moved their eyes to any of the objects other than the color singleton target. Across the two experiments, none of the younger or older subjects reported the appearance of the abrupt-onset distractor and only 2 younger subjects in the first experiment reported that they had observed anything unusual (which they claimed to have been an infrequent change of color in one of the distractors, which never occurred). None of the subjects thought they had misdirected their gaze on more than a few trials.

At first glance, subjects' lack of awareness of the appearance of the onset distractor and their direction of gaze might appear surprising, as it did to us in our previous study with younger adults (Theeuwes, Kramer, Hahn, & Irwin, 1998). However, there are several precedents for such reports. For example, Yantis and Jonides (1984; also see Jonides & Yantis, 1988) have reported that although all of their observers were aware of color and luminance

[6] An interesting question concerns whether the phenomenon that we have observed in the present experiments (i.e., the high proportion of misfixations on the onset distractor) is the result of overt or both overt and covert misallocation of attention to the location of the onset distractor. Folk and Remington (1998) have recently argued that there appear to be at least two forms of attentional capture, a spatial shift of attention to the location of a singleton distractor and a nonspatial distraction effect. Clearly, observers moved their eyes to the location of the onset distractor on a substantial proportion of the trials in our paradigm. Therefore, overt attention, as indicated by the eye movement data, was spatially misdirected in our studies. Is covert attention also misallocated to the distractor in our paradigm? Although the data obtained in the present experiments do not adequately answer this question, we have recently obtained a response compatibility effect when response-compatible and response-incompatible letters (i.e., letters that appear in the onset distractors that are a *c* or reversed *c*) appear in the onset distractor (Theeuwes, Kramer, Hahn, Irwin, & Zellinsky, 1999). Previous researchers have interpreted the presence of a response compatibility effect as evidence for the spatial allocation of attention (Eriksen & St. James, 1986; Eriksen & Yeh, 1985; however, see Lavie, 1995). Second, although it is certainly possible to shift attention in the visual field in the absence of eye movements (Klein & Farrell, 1989; Posner, 1980), recent studies have shown that the reverse relationship, moving the eyes without shifting spatial attention, may not be possible (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995). Therefore, given the current state of knowledge, it would appear most parsimonious to assume that both covert and overt attention was captured by the appearance of the sudden-onset distractor in our experiments.

differences in their search displays, none of the observers noticed the appearance of sudden onsets. Indeed, the lack of awareness in Yantis and Jonides's studies is perhaps even more surprising than our results because in their studies the onset object occasionally served as the target.

McCormick (1997) has recently reported the results of an ingenious set of studies in which subjects were instructed to shift their attention contralateral to the location of a peripheral cue to prepare for a target. For cues that were perceived, cuing benefits (i.e., reduced RTs) were largest contralateral to the location of the cue. However, for dim cues that observers were unaware of, cuing benefits were obtained only in locations next to the cue. These results, like those reported by Yantis and Jonides and the present findings, suggest that attentional capture can occur in the absence of subjective awareness. Furthermore, our results extend these earlier observations in two ways: First, they suggest that people are no more aware that they have misdirected their eyes to attention capturing events than they are that performance is disrupted by such events. Second, our results suggest that this lack of awareness of the appearance of abrupt-onset distractors is age invariant.

Although our data provide new insights into oculomotor and performance consequences of attentional capture from young adulthood to old age, there are a number of interesting and important unanswered questions. For example, although younger and older adults show similar performance and oculomotor responses to the appearance of a task-irrelevant distractor that appears simultaneously with a color change that defines the location of a target, one wonders whether the temporal dynamics of capture is age invariant. In a previous study (Theeuwes, Kramer, Hahn, Irwin, & Zelinsky, 1998) it was found that the proportion of trials on which the eyes were misdirected to an onset distractor decreased from approximately 35% when the onset occurred simultaneously with the color change that defined the target to approximately 5% when the onset appeared 150 ms after the target. Interestingly, however, substantial performance disruption by the onset distractor was observed at the 150-ms stimulus onset asynchrony. Given previous reports of a differential time course of facilitatory effects in attentional cuing tasks for younger and older adults (Hartley, 1992; Madden & Plude, 1993), it appears conceivable that attentional capture might be more long-lasting for older than for younger adults. Indeed, this could be the result of either a requirement for increased time to shift attention and program an eye movement to a target location or a decrease in the effectiveness of inhibitory processes needed to suppress the capture of attention by abrupt onsets. In any event, potential age-related differences in the temporal dynamics of attentional capture are an important topic for future research.

Another important issue concerns the apparent discrepancy between our findings of age-equivalent attention capture effects and age-related decrements reported by Olincy, Ross, Young, and Freedman (1997) in an antisaccade task. The antisaccade task, first introduced by Hallett in 1978 (also see Hallett & Adams, 1980), involves the presentation of an abrupt-onset stimulus to the right or left of fixation in an otherwise empty visual field. The subject's task is to detect the onset using peripheral vision and rapidly look in the opposite direction. Performance on the antisaccade task, which clearly requires that subjects suppress a reflexive eye movement toward the onset stimulus while programming and executing a goal-directed saccade in the opposite direction, is dramatically affected by lesions in the frontal and prefrontal regions of the brain that are involved in the programming of goal-directed saccades (Guitton et al., 1985; Pierrot-Deseilligny, Rivaud, & Gaymard, 1991; Pierrot-Deseilligny; Rivaud, Gaymard, Muri, & Vermersch, 1995). Patients with frontal lobe damage have great difficulty inhibiting reflexive saccades to the onset stimulus, typically making saccades to the onset on 70%–80% of the trials (as compared with approximately 10% misfixations by healthy individuals).

Given the often-reported changes in frontal lobe morphology and decreases in metabolism during the course of normal aging (Azari et al., 1992; Coffey et al., 1992; West, 1996), Olincy et al. (1997) examined potential age-related changes in the performance of the antisaccade task. Three important findings were obtained: First, the proportion of misfixations on the onset stimulus increased linearly from approximately 10% for 20-year-olds to 50% for 80-year-olds. Second, the latency on those trials on which the eyes did move in the opposite direction of the stimulus increased substantially with aging. Third, the latency of eye movements for correct trials on the antisaccade task was disproportionally increased for older adults relative to the latency on trials in which subjects were instructed to move their eyes to the flashed stimulus. On the basis of these results, the authors concluded that the inhibitory processes necessary for the suppression of eye movements to task-irrelevant events is compromised during the course of normal aging.

At first glance, the results of the Olincy et al. (1997) study with the antisaccade task appear to be inconsistent with our results and conclusions with the attentional capture paradigm. Why should older adults show dramatically inferior performance on the antisaccade task while displaying performance equivalent to that of younger adults in our paradigm? Although the answer to this question must await further research, we have several hypotheses. First, it is conceivable that fewer inhibitory resources are required to suppress the movement of attention and the eyes to an abrupt-onset distractor in a display with many nononset distractors (i.e., the other letters in the circles that were created by the removal of segments of the premask figure eights) than in displays with few nononset (old) distractors. Indeed, Martin-Emerson and Kramer (1997) reported, in a series of studies, that the ability of an abrupt onset to capture attention in an obligatory fashion decreases with increases in the number of other objects in a display. They suggested that this effect was the result of increased competition of the nononset objects and onset object for attention as more objects were available in a display. In such a case, one might expect a systematic decrease in the need for inhibitory resources with increases in the number of objects in a display. This hypothesis could be tested by examining whether age-related differences in performance disruption and misfixations increase in response to the appearance of a task-irrelevant onset with decreases in the number of other (nononset) objects in the display. If so, such results would suggest only limited age-related sparing of the inhibitory processes needed to suppress the capture of attention by the appearance of task-irrelevant objects in the visual field.

Another possible explanation for the age-equivalent performance in our task and the decreased performance exhibited by the older adults in the antisaccade task (Olincy et al., 1997) concerns the subjects' level of awareness of the attention capturing objects. As we previously mentioned, observers were generally unaware of the presence of the abrupt-onset distractor in our attentional capture paradigm. On the other hand, in the classic antisaccade paradigm, observers must detect the luminance increment stimulus

before programming and executing an eye movement in the opposite direction. Therefore, subjects must be aware of the potentially attentional capturing abrupt-onset stimulus in the antisaccade task.

Given previous reports of age-related sparing on learning and memory tasks that presumably do not require conscious recollective processes and age-related deficits on learning and memory tasks that do require such processes (Craik & Anderson, in press; Craik & Jacoby, 1996; Schacter, Kihlstrom, Kaszniak, & Valdiserri, 1993), it is conceivable that the degree to which age-related differences in attentional capture are observed might be a function of subjects' level of awareness of the attention-capturing stimuli. That is, equivalent performance for younger and older adults might have been observed in our paradigm precisely because they were unaware of the attention-capturing abrupt stimulus. In such a case, implicit inhibitory processes, that is, those processes that are relatively age invariant, might be called on to suppress eye movements to the abrupt-onset distractor. On the other hand, subjects' awareness of the abrupt onset in the antisaccade paradigm might result in the use of explicit inhibitory processes (i.e., just those processes that show age-related deficits). This "level of awareness" hypothesis could be tested by explicitly pointing out to subjects that onset distractors do occur on a large proportion of the experimental trials (perhaps by slowing down the display presentation rate so that such events can be easily perceived) and instructing them to do their best to avoid looking at these task-irrelevant objects. If the level of awareness hypothesis is accurate, we would expect to observe a larger proportion of misfixations (and performance disruption) for older than for younger adults on this version of our paradigm.

In summary, although there are still a number of important unanswered questions concerning the boundary conditions on the age equivalence that we have observed in the present studies, the results still provide important insights into the attentional and oculomotor processes that underlie the phenomenon of attentional capture from young adulthood to old age. Indeed, the fact that the eyes are misdirected on approximately 40% of the trials on which a task-irrelevant abrupt-onset occurs, for both younger and older adults, has important theoretical and practical implications for the understanding of visual search in the natural environment.

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